Bacteria Loads from Point and Nonpoint Sources in an Urban Watershed

Tina M. Petersen[1]; Hanadi S. Rifai[2]; Monica P. Suarez[3]; and A. Ron Stein[4]

Abstract: A pathogen impaired watershed in Houston, Tex., was studied to assess the spatial and temporal nature of point and nonpoint bacterial load contributions. End-of-pipe sampling at wastewater treatment plant effluent and storm sewers discharging under dry weather conditions was undertaken. Relatively low concentrations of *E. coli* were found in wastewater treatment effluent, with a geometric mean of 5 MPN/dL, while dry weather storm sewer discharges exhibited a geometric mean concentration of 212 MPN/dL. Loads from both point and nonpoint sources of *E. coli* were calculated and compared to in-stream bacteria loads. Nonpoint loads were estimated using an event mean concentration approach on an annual basis. Nonpoint source (NPS) loads were the primary source of bacteria loading to the bayou. Wastewater treatment plant and dry weather storm sewer loads, however, dominated in dry weather conditions. While NPS loads remained relatively constant from headwaters to the mouth of the bayou, point source loads exhibited greater spatial variability depending on the distribution of the discharging pipes. The study points to the need for spatial and temporal considerations in managing bacterial pollution in streams.

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Introduction

An alarming number of watersheds nationwide are currently considered pathogen contaminated by the United States Environmental Protection Agency (USEPA). In Texas, pathogen pollution was the primary cause of impairments on the 2000 303(d) list. The 303(d) list is named after the section of the Clean Water Act that requires states to maintain a list of streams that do not meet water quality standards. Although the National Pollutant Discharge Elimination System (NPDES) has controlled point sources to some degree, many streams and water bodies still do not meet the USEPA's goals of "fishable and swimmable" waters. The National Research Council (NRC) assessment of the total maximum daily load (TMDL) program indicated that this focus on point sources left nonpoint source (NPS) pollution unchecked and unregulated (National Research Council 2001). It is, however, very difficult to determine the relative contribution of point and nonpoint sources to bacterial quality of surface water. This is because of the diverse nature of bacterial sources within a watershed and the many factors that influence the ultimate fate of the pathogens once they are released into the environment.

Point sources are those that can be traced back to a pipe and are one of the largest potential sources of human enteric bacteria. While recent studies have indicated that wastewater treatment plants (WWTPs) are not a major source of indicator bacteria loading (Davis et al.1995; Baudart et al. 2000; Haack et al. 2003), questions still remain as to whether pathogenic organisms are present in effluent in a viable-but non-culturable state and become revived in a nutrient-rich receiving stream (Rockabrand et al. 1999). Leaks in sewer collection systems have also been implicated as potential point sources, especially during dry weather when the lowered water table draws out sewage from leaking pipes (Davis et al. 1995; Whitlock et al. 2002). Storm drains have additionally been recognized to be potential dry weather sources (Gannon and Busse 1989; Haack et al. 2003).

Nonpoint sources of pollution include stormwater runoff from pervious and impervious surfaces, failing septic systems, and direct deposition of animal feces. Much recent research has focused on runoff from urban transportation systems (Characklis and Wiesner 1997; Barrett et al. 1998; Deletic and Maksimovic 1998; Irish et al. 1998; Wu et al. 1998; Drapper et al. 2000), but these discussion rarely focus on bacteria. Studies focusing exclusively on bacteria have shown that these types of pollutants are especially difficult to trace in urban areas because the exact source of the bacteria in the runoff is often unknown (Feeney 1998; Grant et al. 2001; Boehm et al. 2002, 2003; Borst and Selvakumar 2003). Bacteria source tracking (BST) methods are currently being employed to identify the specific sources of bacteria in runoff. Results point to diverse and widespread sources that include wildlife and domestic animals, such as raccoons, waterfowl, and dogs (Weiskel et al. 1996; Grant et al. 2001; Schiff and Kinney 2001; Simpson et al. 2002; Whitlock et al. 2002).

[1]PhD Candidate, Dept. of Civil and Environmental Engineering, Univ. of Houston, Houston, TX 77204-4003.

[2]Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Houston, 4800 Calhoun, N107 Engineering Building 1, Houston, TX 77204-4003 (corresponding author). E-mail: rifai@uh.edu

[3]Researcher, Dept. of Civil and Environmental Engineering, Univ. of Houston, Houston, TX 77204-4003.

[4]Project Manager, Texas Commission on Environmental Quality, 12100 Park 35 Circle, Austin, TX 78753.

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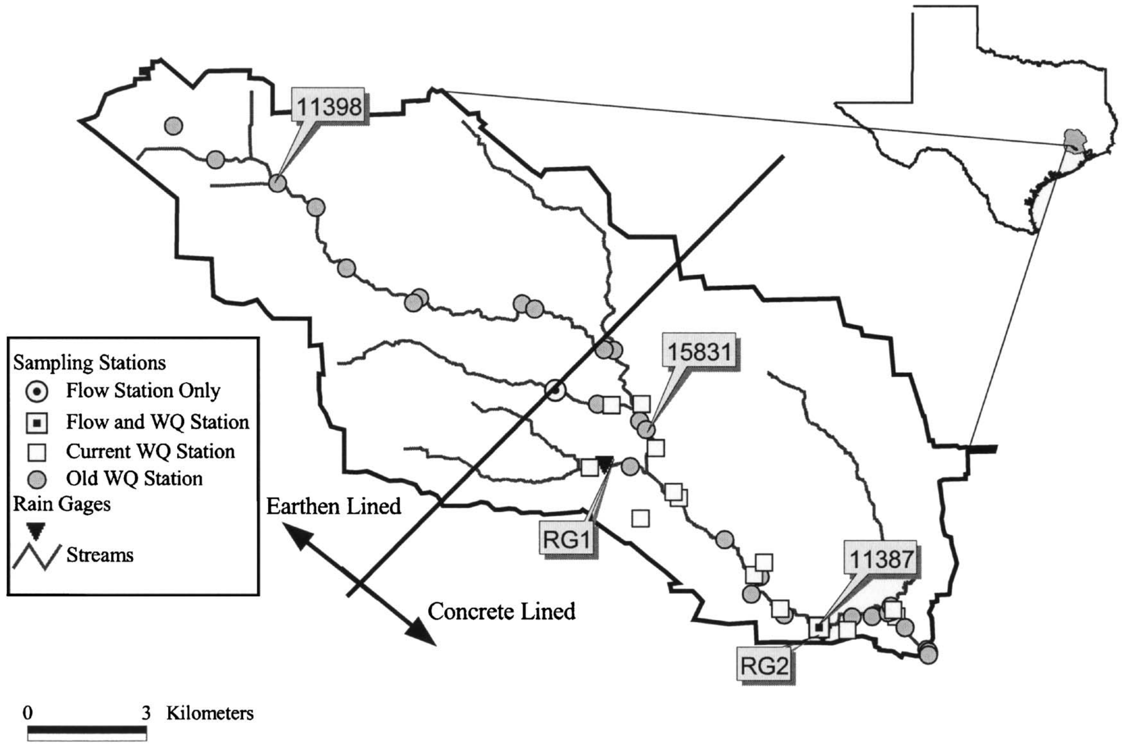

Fig. 1. Selected water quality gauges in Whiteoak Bayou Watershed

Once within waterbodies, enteric bacteria can survive and reproduce in rich organic sediments (Gerba and Mc Leod 1976; Erkenbrecher 1981; Hood and Ness 1982; Stephenson and Rychert 1982; Davies et al. 1995; Buckley et al. 1998; Obiri-Danso and Jones 2000; Palmer 2000). These bed sediments may function as a source of bacteria to the overlying water through resuspension initiated by fluid shear exerted on unconsolidated bottom sediments through either wave action or increased stream velocities (Pettibone et al. 1996; Crabill et al. 1999; Baudart et al. 2000; Solo-Gabriele et al. 2000; Desmarais et al. 2002; Fevre and Lewis 2003).

Given the complex nature of these various sources, and especially within the context of TMDLs, studies are needed to understand the relative contributions from point and nonpoint sources. Additionally, it is important to understand the variations in point and nonpoint sources over the course of a given year and their variation throughout a particular watershed. Since both point and nonpoint sources are influenced by land use and rainfall, their impacts on water quality in a stream will likely change over time and with distance along a stream.

This paper presents a study of point and nonpoint sources of *Escherichia coli* (EC) and fecal coliform (FC) in Whiteoak Bayou, a stream in an urbanized watershed in Houston, Tex. Whiteoak Bayou typically exhibits indicator bacterial concentrations that exceed the standard by as much as ten times. Point sources are estimated using data from an extensive sampling program targeting end-of-pipe discharges, including wastewater (WWTP) effluent and dry weather storm sewer (DWSS) flows. The NPS loads are estimated using an event mean concentration (EMC) based approach. Loads from point sources as well as from NPS are calculated at various points within the watershed annually and on a monthly basis for 1 year. The estimated loads are compared to in-stream loads to better understand their spatial and temporal variations as well as their relative impacts on bayou quality.

Whiteoak Bayou

The Whiteoak Bayou watershed covers a total of 288 km^2 within the San Jacinto River basin in Texas (Fig. 1). Soils in the watershed are resistant to infiltration and the watershed slopes are nearly level, ranging from 0 to 3%. The climate is classified as coastal temperate, receiving approximately 1.27 cm (50 in.) of rain throughout the year.

The hydrology of the bayou is controlled in large part by the surrounding land use, which is primarily urban. The watershed is more developed in the lower reaches. The 45 km long bayou was channelized in the late 1960s and partially concrete lined to provide improved flood control (Fig. 1). Land use in the Whiteoak Bayou watershed has changed rather dramatically over the past 30 years. In the late 1970s, the upper watershed was largely agricultural, with some wooded areas along the bayou. Significant development occurred in the 1980s and by 1992, the upper watershed was evenly split between agriculture, woody and developed areas. More recent land use/land cover data show the upper watershed to be almost entirely urbanized, with minor regions of agriculture. The lower watershed (where the bayou is concrete lined), on the other hand, experienced growth very early on in Houston's history. By the late 1970s, the lower watershed was already almost entirely urbanized, with the majority of the land use being residential.

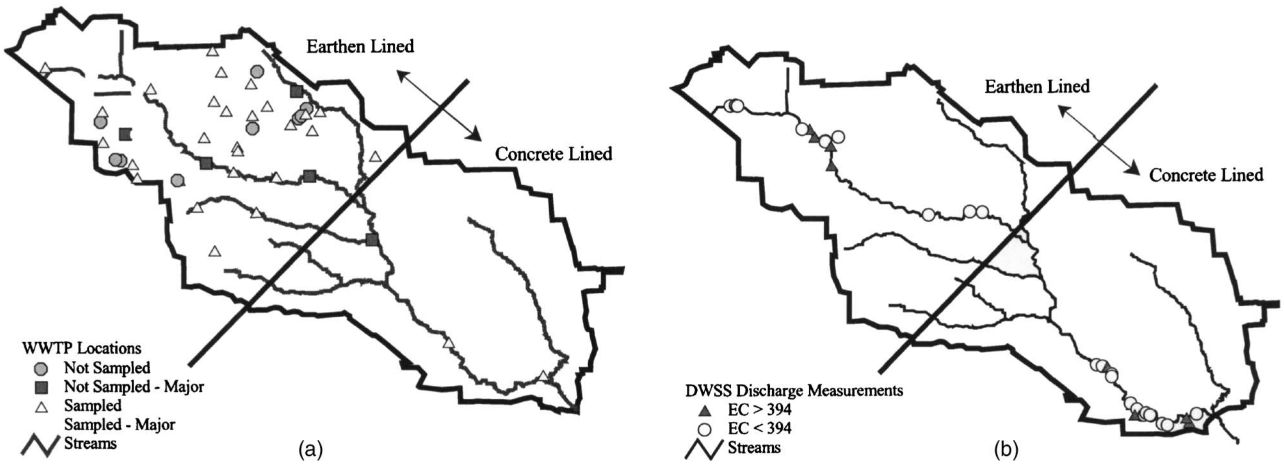

Fig. 2. (a) Sampling locations for wastewater treatment plants and (b) dry weather storm sewer discharges

Flow in the bayou consists of runoff from the surrounding watershed and domestic WWTP effluent discharges along with a few industrial WWTP discharges. At capacity, the bayou carries approximately 752.9 m^3/s based on calculations performed using FEMA *HEC-RAS* models, while the median flow is around 1.42 m^3/s at the USGS gaging station located at Station 11387. The WWTP effluent constitutes a significant portion of the flow in the bayou, especially when flow is less than the median flow. There are currently 50 operating WWTP plants in the watershed, eight of which are classified as industrial dischargers. All industrial WWTPs lie in the drainage area above Station 11387 (see Fig. 1). Of the domestic dischargers, 11 have major NPDES permits, meaning that they are permitted for greater than 1 MGD flow. The total permitted flow from all domestic dischargers is 2.23 m^3/s (50.8 MGD) and from industrial dischargers is 7.75×10^{-3} m^3/s (0.177 MGD). The average self-reported daily effluent for the 50 plants calculated on a monthly basis between 1990 and 2000, totaling approximately 0.857 m^3/s (19.6 MGD), is slightly less than the 2 year, 7 day minimum flow ($7Q2$) of 0.867 m^3/s (19.8 MGD). No WWTPs are located in the drainage area below the USGS gauging station located at Station 11387.

In addition to effluent discharges, there are over 25,000 storm sewer pipes in the watershed, with some dating back to 1913 according to City of Houston Geographic Information System records. Even though these pipes would not be expected to discharge to the bayou during dry weather, in fact they do. This is because of illegal connections, dumping and leaks from the sanitary sewer infrastructure and water lines. These flows are expected to be fairly small in magnitude; however, their contribution to bacterial pollution is quite significant as will be seen in this study.

Runoff is fairly substantial [(1.6×10^{-3} m^3 during an average year, from Newell et al. (1992)] because of the amount of rainfall received and the low infiltration potential of the soils in the watershed. Additionally, the weather is typically dry, with over 40% of the year exhibiting 3 or more consecutive days without rain. Water quality in the bayou has been monitored since 1973 at a number of sampling stations by the Texas Commission on Environmental Quality, the City of Houston, and Harris County, as shown in Fig. 1. Active stations are typically monitored every month and data from these monitoring stations indicate elevated EC and FC throughout the year as will be discussed later in the paper. Sampling in this study was focused on estimating point source loads to the bayou. This involved sampling WWTP effluent and DWSS discharges during the summer of 2001 through early 2002.

Methods and Materials

Sampling Wastewater Treatment Plant Discharges

A total of 36 WWTPs were sampled [Fig. 2(a)], with the effort focusing on the smaller wastewater treatment plants (generally less than 1 MGD) because major plants are staffed with full-time operators and generally have more reliable chlorine dosing systems. Each plant was sampled twice over the course of one day from July through October 2001: once in the early morning and once at mid-morning to evaluate the potential water quality changes due to diurnal variations in flow. Samples for all plants were collected past the chlorine contact chamber, just after the weir, using a sterilized 1 L bottle. Fecal coliform, and *E. coli* samples were poured directly into 100 mL Whirl-Pak Thio-Bags (Nasco, Fort Atkinson, Wis.) from the 1 L bottle, each bag containing a 10 mg non-nutritive sodium thiosulfate pill to eliminate any potential chlorine in the sample. Total suspended solids (TSS) samples were poured directly into a 250 mL plastic bottle. The Whirl-Pak bags and TSS bottles were immediately placed on ice. Samples for ammonia and orthophosphorous were poured from the sterilized 1 L polypropylene bottle into a 120 mL disposable plastic bottle also treated with sodium thiosulfate. Individual analyses for ammonia and orthophosphorous were run using the Test'N'Tube methods from HACH and read on a HACH DR/850 colorimeter (HACH, Loveland, Colo.). The sample for chlorine residual was poured from the sterilized 1 L bottle into a glass 10 mL HACH sample cell that had been pretreated with bleach to remove any chlorine demand. The glass sample cell was rinsed twice with the sample water prior to collecting the sample for analysis. A probe (Model 600XL, YSI Inc., Yellow Springs, Ohio) was used to

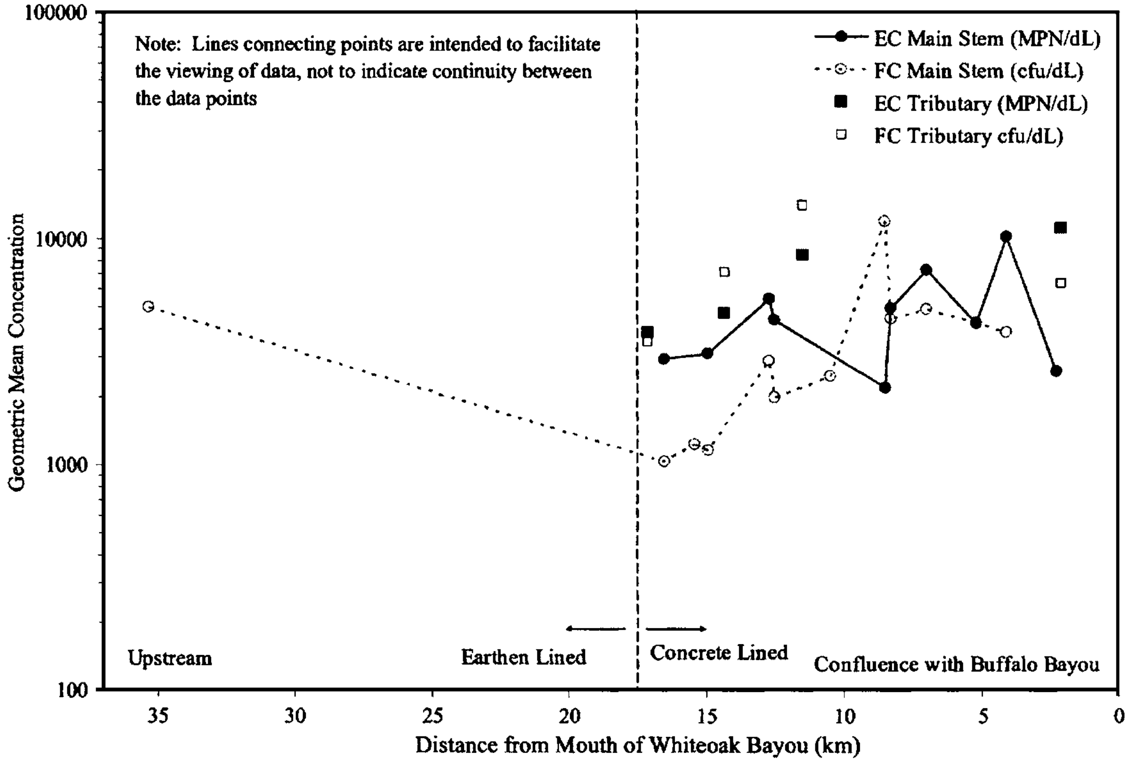

Fig. 3. Bacteria concentrations longitudinally along Whiteoak Bayou

collect dissolved oxygen, turbidity, pH, conductivity, and temperature readings. Flow measurements were taken using the facility's automated flow meter, a staff gauge placed in the chlorine contact chamber or the YSI probe. For quality assurance purposes, duplicate samples were collected every tenth sample for all bacteria and HACH analyses.

Sampling Dry Weather Storm Sewer Discharges

On-foot reconnaissance was undertaken during dry weather conditions to locate all discharging pipes within the watershed. A dry weather condition was established when three days had passed without any rainfall. A total of 52 pipes [as shown in Fig. 2(b)] were sampled once between November 2001 and May 2002. Discharging pipes were first screened for chlorine to avoid collecting wastewater effluent. Discharges with less than 1 mg/L total chlorine were collected in 1 L sterilized bottles. Chlorine residual, ammonia, and orthophosphorous readings were taken using the HACH DR/850 instrument and the YSI sonde was used to collect dissolved oxygen, turbidity, pH, conductivity, and temperature readings. Flow data were recorded by collecting the flow in a graduated beaker and timing for one minute or until the flow reached 300 mL, whichever occurred first. For flows that filled the beaker in less than a few seconds, a bucket was employed rather than the beaker to contain the flow for a minute. The volume in the bucket was then measured and used for flow rate determination.

Total Coliform/Escherichia coli/Fecal Coliform Enumeration

The EC analyses were performed with a defined substrate test using the IDEXX method Colilert reagent (IDEXX Laboratories Inc., Westbrook, Me.) implemented in a 100 well Quanti-tray format. Samples were kept on ice and processed within 8 h of collection. Two to three dilutions were made for each sample, and each dilution was analyzed at least in duplicate. The trays were incubated at 35.5°C for at least 24 h but not more than 28 h. After removal from the incubator, the trays were read. Yellow wells indicated the presence of total coliform (TC) and fluorescence under long-wave ultraviolet light indicated the presence of EC. The number of positive wells was tabulated and correlated to a concentration using the IDEXX-supplied MPN chart. Quality control included analysis of laboratory blanks every time an IDEXX analysis was run and analysis of reference cultures obtained from IDEXX every 3 months. The FC analyses were conducted at a commercial laboratory using USEPA Standard Method 9222-D.

Results

Bacteria in Bayous

Over 90% of the 2,381 FC samples collected from 1971 to 2001 have exceeded the single sample 400 cfu/dL standard for FC in fresh water. Samples were collected monthly by the sampling agencies during typical ambient conditions, meaning that runoff conditions were generally avoided. Starting in 2000, the State of Texas shifted from fecal coliform as an indicator to EC. The EC data gathered since 2000 indicated that over 95% of the 231 samples exceeded the single sample standard for EC of 394 MPN/dL. The geometric mean of the 147 EC samples is around 4,664 MPN/dL, over ten times the 394 MPN/dL standard.

The data in Fig. 3 show the geometric mean EC and FC concentrations between 1995 and 2003 longitudinally along the bayou. Sample sizes ranged from 6 to 80 samples. Both EC and

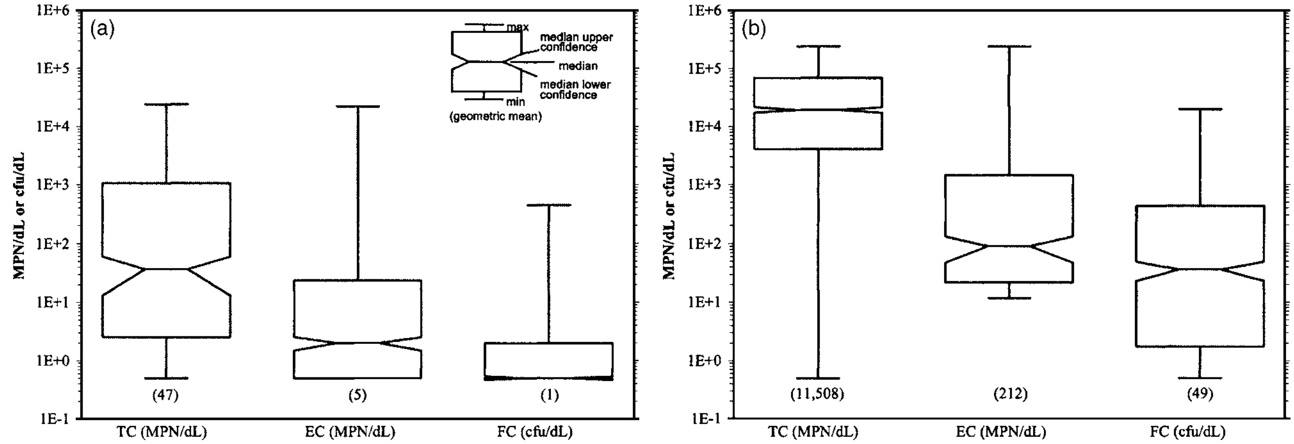

Fig. 4. Bacteria results from (a) effluent and (b) dry weather storm sewer sampling

FC demonstrate a trend of increasing concentrations from upstream to downstream. The EC concentrations have a similar trend, although the geometric mean concentrations show much more variation than the FC geometric means, possibly due to the smaller dataset. It is noted, however, that, there is some uncertainty in EC and FC levels in the earthen-lined part of the bayou, due to the lack of data in that part of the stream. The lack of historical data at that uppermost station stems from the State of Texas and City of Houston monitoring program not conducting water sampling in that region.

Bacteria in Wastewater Treatment Plant Effluent

The results from effluent sampling generally showed that bacteria levels in effluent were low [Fig. 4(a)], indicating that WWTPs may not be a significant source of bacteria to the bayou relative to other sources. The mean measured EC concentration was 498 MPN/dL, while the geometric mean was much lower at 5 MPN/dL. Only 6% of the EC samples and 1% of the FC effluent samples exceeded the Texas Water Quality Standards for a single sample (394 MPN/dL for EC and 400 cfu/dL for FC).

The flow at the sampled wastewater facilities ranged from 1.8×10^{-7} m^3/s (4.1×10^{-6} MGD) to 0.197 m^3/s (4.5 MGD) (Table 1). Dissolved oxygen (DO) was fairly consistent for most plants, around 7.5 mg/L, while nutrients varied, with mean concentrations found at 4.3 and 11.9 mg/L, for ammonia and orthophosphorous, respectively. The means for morning and mid-morning sampling measurements were compared using a paired-sample *t*-test. Results showed no significant differences between the means ($\alpha<0.05$) except for flow, chlorine, fecal coliform, and temperature. The first three were higher in the early morning while the last was higher at mid-morning, as would be expected during the summer. Correlations were examined for bacteria concentrations with the various physical and chemical parameters using a parametric, bivariate correlation. Strong linear relationships (indicated by a high Pearson's correlation coefficient) were found between log(TC) and log(EC) and also conductivity and pH.

Bacteria in Dry Weather Storm Sewer Discharges

The concentrations of EC and FC found in DWSS discharges were much higher than those observed at WWTPs, although flows associated with these discharges were generally much smaller, on the order of 1.5×10^{-6} m^3/s (3.4×10^{-4} MGD) to 9.2×10^{-3} m^3/s (0.21 MGD) as shown in Table 1 and Fig. 4(b). The geometric mean concentration for EC was 212 MPN/dL and

Table 1. Results from Effluent and Dry Weather Storm Sewer Sampling

	Residual chlorine (mg/L)	Flow		Dissolved oxygen (mg/L)	Turbidity (NTU)	Ammonia (mg/L)	*o*-phosphorous (mg/L)	Total suspended solids (mg/L)
		m^3/s	MGD					
(a) Wastewater treatment effluent								
Mean	2.3	1.7×10^{-2}	0.40	7.6	3.1	4.3	11.9	5.6
Median	0.9	6.0×10^{-3}	0.14	7.5	1.6	0.05	10.8	4.1
Standard deviation	3.6	2.96×10^{-2}	0.68	1.8	3.3	14.2	9.8	4.9
Maximum	16.6	0.20	4.5	13.2	14.0	82	57	23.8
Minimum	<0.01	1.8×10^{-7}	4.1×10^{-6}	2.3	0.0	<0.01	<0.03	0
(b) Dry weather storm sewer pipes								
Mean	0.2	1.0×10^{-3}	0.02	9.17	17.2	0.48	1.54	13.4
Median	0.1	6.6×10^{-5}	1.5×10^{-3}	9.44	5.1	0.20	0.46	6.8
Standard deviation	0.3	1.8×10^{-3}	0.04	2.39	41.4	0.93	2.87	20.1
Maximum	1.6	9.2×10^{-3}	0.21	13.53	268.6	5.50	>13.75	125
Minimum	<0.01	1.5×10^{-6}	3.4×10^{-5}	2.03	0	<0.02	<0.05	1

Note: Values less than the detection limited treated as 1/2 the detection limit.

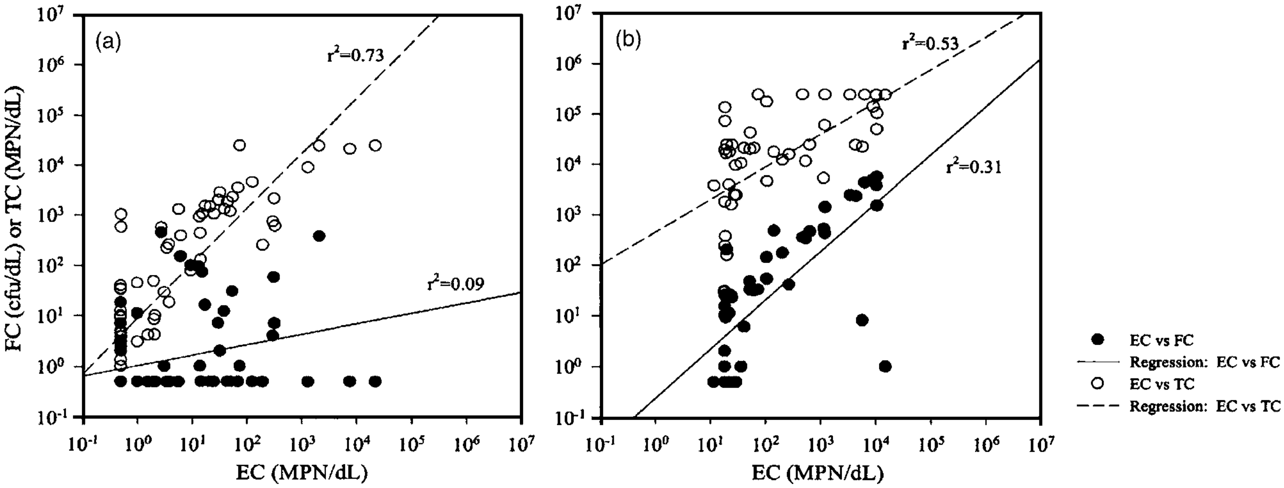

Fig. 5. Relationships between bacterial groups in (a) effluent and (b) dry weather storm sewer discharges

49 cfu/dL for FC. Over 39% of all collected samples exceeded the EC single sample water quality standard and 28% exceeded the FC single sample standard.

Total chlorine samples were screened to be less than 1 mg/L for the DWSS dischargers, but chlorine residuals were also found to be generally very low. Turbidity and TSS were higher than those seen with effluent with means of 17.2 NTU and 13.4 mg/L, respectively. The DO was generally much higher than concentrations seen at WWTPs, with a mean of 9.17 mg/L. Bacteria concentrations in storm sewer discharges were strongly correlated with ammonia and phosphorous. Additionally, the correlations between the different bacterial measurements (EC versus FC, EC versus TC) had higher Pearson's coefficients than those observed with the WWTP sampling.

It is noted that while TC was always higher than EC, FC was often lower than EC for both effluent and DWSS discharges. The FC concentrations were expected to be greater than EC concentrations, as EC are a subset of FC bacteria. This observation has been reported in the literature and is attributed to differences in the analytical methods for EC and TC (i.e., MPN versus membrane filtration) and possible false positives and negatives (Gannon and Busse 1989; Elmund et al. 1999; Yakub et al. 2002). The data in Fig. 5 show the relationships between the various bacteria measures for both effluent and DWSS discharges. As can be seen, TC and EC were strongly correlated in both types of samples (r^2=0.73 and 0.53, respectively) while FC and EC were poorly correlated for effluent (r^2=0.09) and weakly correlated for DWSS discharges (r^2=0.31).

The EC concentrations measured in WWTP effluent and DWSS discharges were used to calculate bacteria loads to Whiteoak Bayou as will be discussed in the next section.

Bacteria Loads From Point and Nonpoint Sources

The relative bacterial contributions from point and nonpoint source pollution sources are essentially unknown in most urban watersheds. Bacterial pollution is characterized in terms of concentrations, but concentration data may be misleading if not related to the flows from each source as loads are additive, while concentrations are not. Loads from bacterial sources are somewhat difficult to estimate due to the low frequency of sample collection. In this study, bacteria loads from both point and nonpoint sources in Whiteoak Bayou were calculated annually and on a monthly basis at three locations in the watershed (see Fig. 1 for locations). Station 11398 (Fig. 1) was chosen because it is the only station in the upper watershed with historical data, while Station 15831 is at the junction of the concrete and earthen lined channels. Additionally, most of the WWTPs are located above Station 15831 and therefore loads at this station would be expected to be more influenced by WWTP effluent. Station 11387 was chosen because it is the only station that has flow readings collected by the USGS and is a frequently sampled station in the watershed. The estimated loads at these stations were compared to the observed load in the bayou.

Point Source Loads

Loads were determined using the measured flows and bacteria concentrations from both effluent and DWSS sampling. Loads from WWTPs were calculated by averaging the load from the morning and mid-morning sampling, while DWSS loads were calculated directly from the field data. It was assumed that flows and concentrations measured in the field were constant for the entire day. This is a large assumption as plant flow changes constantly and presumably so does EC. This assumption is currently being evaluated through a sampling program to examine intraplant variation in flow and EC concentration. Table 2 presents a summary of the results. The load entering Whiteoak Bayou at Station 11387 from all upstream WWTP dischargers was

Table 2. Wastewater Treatment Plant and Dry Weather Storm Sewer Loads from Field Sampling Data

Station	Flow range (m^3/s)	Total flow (m^3/s)	*E. coli* load (MPN/day)
(a) Wastewater treatment plant			
11398	9.0×10^{-5}–0.06	0.150	1.3×10^{9}
15831	1.8×10^{-7}–0.20	0.538	2.09×10^{12}
11387	1.8×10^{-7}–0.20	0.579	2.09×10^{12}
(b) Dry weather storm sewer			
11398	1.85×10^{-3}–0.01	0.001	2.11×10^{7}
15831	1.52×10^{-4}–0.01	0.002	1.08×10^{9}
11387	3.42×10^{-5}–0.21	0.002	1.98×10^{11}

Note: Totals for flow do not include plants that were not sampled.

Table 3. Fecal Coliform Event Mean Concentrations (cfu/dL) for Houston, Texas

	Land use[a] (m^2)	Newell et al. (1996)	Houston MS4 Permit (1992–2002) August–November	December–February	March–July	San Antonio MS4 Permit[b]	Dallas/Ft. Worth MS4 Permit[b]	Corpus Christi MS4 Permit[b]
Residential	1.60E+08	22,000	**52,342**	**26,963**	**40,850**	37,500	20,000	40,500
Commercial	3.01E+07[c]	22,000	**105,158**	**16,918**	**95,776**	6,150	6,900	14,800
Industrial	—	—	35,846	201,061	63,034	—	9,700	31,500
Transportation	—	—	125,500	155,714	483,877	—	53,000	—
Cropland	5.31E+07	**2,500**	—	—	—	—	—	—
Rangeland	—	**2,500**	—	—	—	—	—	—
Wetlands	2.58E+06	1,600	**74,150**	**15,550**	**14,895**	—	—	—

Notes: Fecal coliform event mean concentrations presented in this table were developed for fecal coliform. A conversion factor to transform fecal coliform data into *Escherichia coli* was done using the ratio of the two water quality standards (126/200=0.63). This approach, although not ideal, has been applied in the past by the USEPA. Bolded event mean concentrations were used for nonpoint source load estimation.

[a]From USGS (2000).

[b]From Baird et al. (1996).

[c]This total is for commercial, industrial, and transportation. Loads were calculated using only commercial event mean concentrations.

calculated to be 2.09×10^{12} MPN/day, while the DWSS load was 1.98×10^{11} MPN/day. The calculated loads from these sources at Stations 15831 and 11398 were lower. In general, flows coming from WWTPs are much larger than those from DWSS, but the concentrations associated with DWSS are much higher. Thus, the two sources have approximately the same relative magnitude at Station 11387. It is noted that the calculated loads do not account for the larger plants that were not sampled. The total load associated with all unsampled plants was calculated to be 9.14×10^{9} MPN/day (using average self-reported flows and the flow-weighted geometric mean EC of the sampled facilities of 19 MPN/dL). This value is small in comparison with the total load from the sampled plants at Stations 15831 and 11387 and was therefore neglected.

Nonpoint Source Loads

Several different methodologies were evaluated for the estimation of nonpoint source build-up of bacteria, including the use of EMCs and the USEPA bacterial indicator tool (BIT). The USEPA BIT (USEPA 2000) focuses primarily on agricultural land uses, and thus was not adequate for the purposes of this highly urbanized watershed. The EMC-based method, therefore, was chosen instead (Schueler 1987; Wong et al. 1997). The EMCs are flow-weighted average concentrations of bacteria in runoff from storm events and have been developed for various land uses. Generally, the method is recommended for small watersheds. However, the method was deemed suitable for providing screening level estimates of NPS loads in Whiteoak Bayou. It should be noted that the EMC approach does not take into account erosional sources of bacteria nor does it account for bacteria die-off and regrowth or settling of bacteria associated with sediment particles. More complex models, such as The Stormwater Management Model (*SWMM*) or the Hydrologic Simulation Program Fortran (*HSPF*), would take some or all of these processes into account and may provide a more accurate estimate of NPS loads. Nevertheless, estimates of NPS in urban areas using both methods (EMC and either *HSPF* or *SWMM*) have been shown to yield results within 1 order of magnitude of each other (Chandler 1994).

The FC EMCs were compiled for several studies across Texas and are presented in Table 3. Data sources included the municipal separate storm sewer system (MS4) permit process and Newell et al. (1992). These studies included EMCs that were collected specifically for Whiteoak Bayou, and the watershed sizes in the two studies were within 4% of each other (286 and 275 km^2). As can be seen in Table 3, EMCs ranged from 1,600 to 201,061 MPN/dL depending on the land use and data source. Land use data (Table 3), obtained from the USGS National Land Cover Dataset (USGS 2000), show that over 53% of the watershed is residential in nature. Rainfall data (from 1971 to 2000) for three seasons (August–November, December–February, and March–July) were obtained from the National Oceanic and Atmospheric Administration for the Houston area and were used to calculate seasonal loads. Rainfall data on a monthly basis were also gathered for two different gauges in the watershed for the year 2000 (see Fig. 1). Average rainfall for the years 1971–2000 was found to be 1.28 m, as shown in Table 4. For RG1 and RG2, the yearly rainfall was 0.83 and 1.16 m, respectively.

The SCS runoff curve number method (NRCS 1986) was used to calculate the runoff depth for each of the three seasons from the watersheds of interest and was multiplied by the area of each land use type to obtain the runoff volume. This volume was multiplied by the EC EMC for each land use to obtain a bacterial load. It is noted that EMCs for residential land uses were used for both low and high intensity residential land use and EMCs for commercial land use were applied to the commercial/industrial/transportation land use category. Values employed in the calculation appear bold in Table 3.

The estimated NPS loads are presented in Table 5. The total EC NPS load was calculated to be 1.59×10^{16} MPN/year for a typical year at Station 11387. The loads during the period of August–November were the highest due to the synergy between elevated precipitation and EMCs during this season, while loads in December–February were the lowest. The calculated loads were comparable to those reported by other studies. For example, the NPS EC load reported by Newell et al. (1992) for a typical wet year was found to be 2.5×10^{16} and 1.8×10^{16} MPN/year

Table 4. Precipitation Totals (m)

	RG1	RG2	1971–2000
August–November	0.42	0.44	0.47
December–February	0.11	0.13	0.27
March–July	0.31	0.59	0.53
Total	0.83	1.16	1.28

Table 5. Estimated *Escherichia coli* Nonpoint Source Loads (MPN/Year) to Station 11387

	Typical year[a]	2000
August–November	9.36×10^{15}	6.62×10^{15}
December–February	2.6×10^{15}	5.66×10^{14}
March–July	3.93×10^{15}	7.08×10^{15}
Total	1.59×10^{16}	1.43×10^{16}

[a]Typical year calculated using average rainfall from 1971 to 2000.

for a typical dry year and that calculated by the Storm Water Management Joint Task Force (2002) was 6.4×10^{16} MPN/year.

Escherichia coli Load in Whiteoak Bayou

The bacteria load in the bayou can vary greatly throughout the year due to changes in flow and ambient bacteria concentration. Bacteria samples are usually collected infrequently in comparison with recorded daily mean stream flows; thus it is necessary to estimate the loads on days when measured EC data are not available. Observed EC loads were calculated at the 11387 gauge (see Fig. 1 for location) using paired EC and daily flow data from the year 2000. A regression equation was developed for Station 11387 to relate observed flows to observed EC concentrations as shown in Fig. 6. This equation was used to determine the EC concentrations when observed data were not available.

The predicted and observed loads are presented in Fig. 7. It can be seen that the predicted EC loads correlate to some degree with the observed loads, although some of the smaller loads were not matched well. The calculated EC loads ranged from 2.9×10^{10} to 4.6×10^{16} MPN/day, while the observed flows ranged from 0.69 to 189 m^3/s during a large summer storm in May. The total yearly load calculated at Station 11387 using this regression equation is 9.2×10^{16} MPN/year.

Low and high flow loads were also estimated at Station 11387 using historical flow data. To develop the high and low flow loads, loads when flow was less than the median were totaled to find the low flow load and loads when flow was greater than the

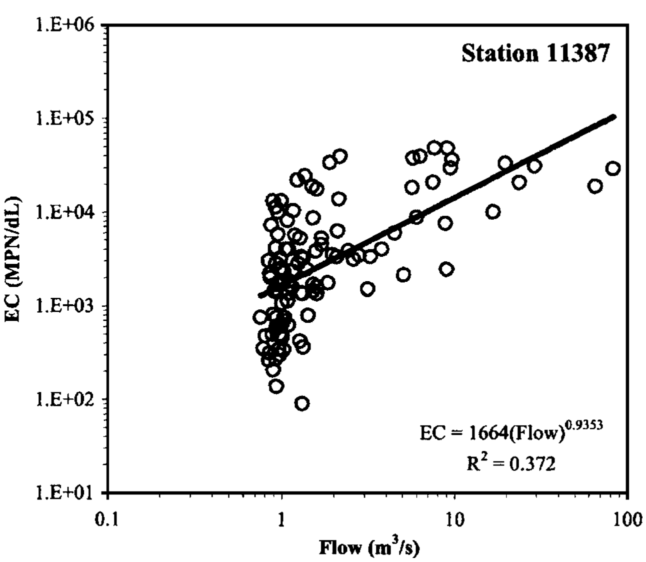

Fig. 6. Regression equation for *Escherichia coli* load estimation at Station 11387

85th percentile (3.99 m^3/s) were summed together for the total high flow load. The load during low flow at Station 11387 was calculated to be 4.0×10^{14} MPN/year, while under high flow conditions the load was calculated to be 4.5×10^{16} MPN/year (Table 6).

Loads at other sites (Stations 11398 and 15831, see Fig. 1 for locations) were also estimated. Since no additional flow gaging stations were located in the watershed on the main stem, the flow at Station 15831 was determined through the use of drainage area ratios to the bayou flow at Station 11387. Station-specific bacteria data along with the scaled back flow from Station 11387 were used to develop the EC load at Station 15831. Station 11398, on the other hand, presented a different situation. The EC data were not available for Station 11398 during this period. Therefore, loads were estimated on the basis of the drainage areas ratios relative to the load at 15831 (Hoos et al. 2000). This approach, however, does not take into account the variability in EC concentrations from the watershed above Station 11398. The results are presented in Table 6. Loads in the bayou under all flow conditions at Station 15831 were 2.4×10^{16} MPN/year, while at Station 11398 loads were 4.5×10^{15} MPN/year. Under low flow conditions, the loads were much smaller at both stations, with loads of 1.5×10^{13} MPN/year for Station 11398 and 8.1×10^{13} MPN/year for Station 15831.

Comparison Between Point and Nonpoint Source Loads

A summary of the estimated loads to the bayou is presented in Table 6. The total load originating from NPS, WWTP, and DWSS flows during a typical year for Station 11387 is 1.5×10^{16} MPN/year while that for 2000 is slightly higher at 3.6×10^{16} MPN/year. Loads at Stations 11398 and 15831 were slightly higher than those at 11387, possibly due to neglecting bacterial die-off in the bayou. In dry weather, point sources (WWTP and DWSS) would be expected to contribute the entirety of the loading. At Station 15831 and 11387, the point source (PS) load is actually greater than the bayou low flow load, while at Station 11398, the bayou load is greater than the PS load. The overestimation at Stations 15831 and 11387 may be because bacterial die-off is being neglected while the underestimation at

Table 6. Comparison of Load Estimates (MPN/Year) in Whiteoak Bayou

	Station ID		
	11398[a]	15831	11387
Nonpoint source load—typical year[b]	2.0×10^{15}	1.1×10^{16}	2.4×10^{16}
Nonpoint source load—2000	9.6×10^{14}	5.1×10^{15}	1.4×10^{16}
Wastewater treatment plant load	4.7×10^{11}	7.6×10^{14}	7.6×10^{14}
Dry weather storm sewer load	7.7×10^{9}	3.9×10^{11}	7.2×10^{13}
Total[c]	9.6×10^{14}	5.9×10^{15}	1.5×10^{16}
Bayou load[d]—all flow	4.5×10^{15}	2.4×10^{16}	9.2×10^{16}
Bayou load[d]—low flow	1.5×10^{13}	8.1×10^{13}	4.0×10^{14}
Bayou load[d]—high flow	4.4×10^{15}	2.4×10^{16}	4.5×10^{16}

[a]See Fig. 1 for station locations.

[b]Typical year calculated using average rainfall from 1971 to 2000.

[c]Sum of nonpoint source-2000, wastewater treatment plant, and dry weather storm sewer load.

[d]Bayou load calculated using data from 2000.

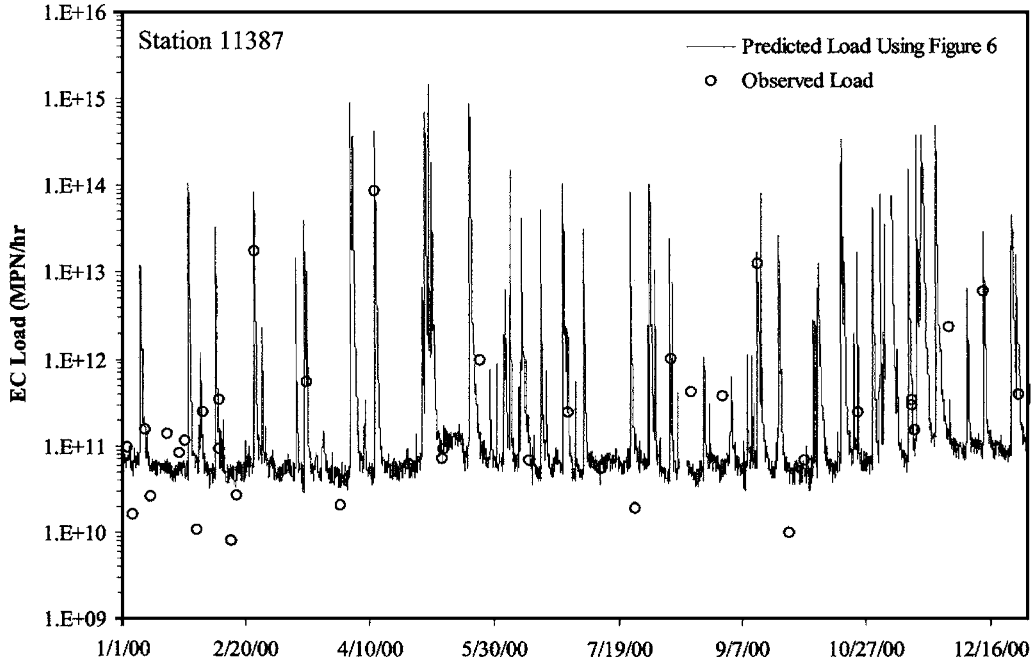

Fig. 7. Observed and predicted in-stream *Escherichia coli* load

Station 11398 may possibly be due to an additional source in the upper watershed. In contrast, the high flow loads at all three stations were about 50% higher than the NPS load which may indicate additional sources of bacteria loading under wet weather are present, such as illegal discharges, WWTP bypasses or resuspension from sediment.

The data in Fig. 8 demonstrate the spatial distribution of the bacterial point and nonpoint source loads across the Whiteoak Bayou watershed. The NPS loads (for the year 2000 as shown in Table 6) increase slightly from the upper to lower watershed, but the WWTP and DWSS loads increase significantly. In the earthen-lined section of the bayou, the NPS load is by far the most significant source of bacteria, approximately 10^5 times that from PS loads. In the lower section, the bayou becomes concrete lined and the WWTP and DWSS loads increase while the NPS load becomes less significant. The WWTP increase is due to high concentrations of indicator bacteria found at several WWTPs just above Station 15831 and due to the presence of a number of WWTPs situated on nearby tributaries entering the main stem of the bayou just above Station 15831. The increases in DWSS loads are due to a number of leaking sewers identified in this study. It is noted that the sewer infrastructure is much older in the lower

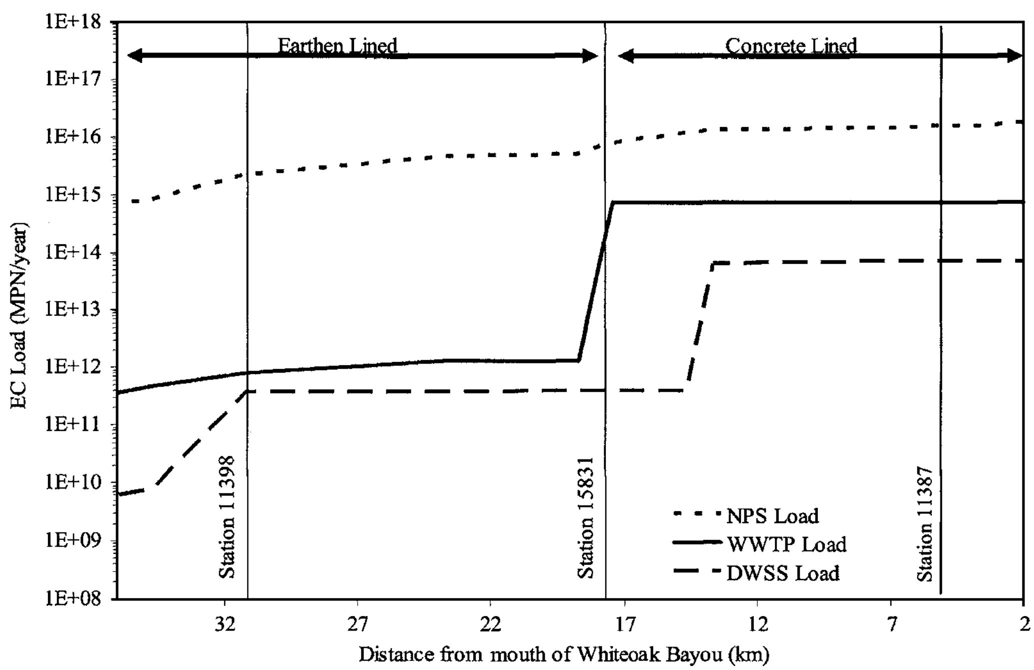

Fig. 8. Longitudinal profile of bacterial loads

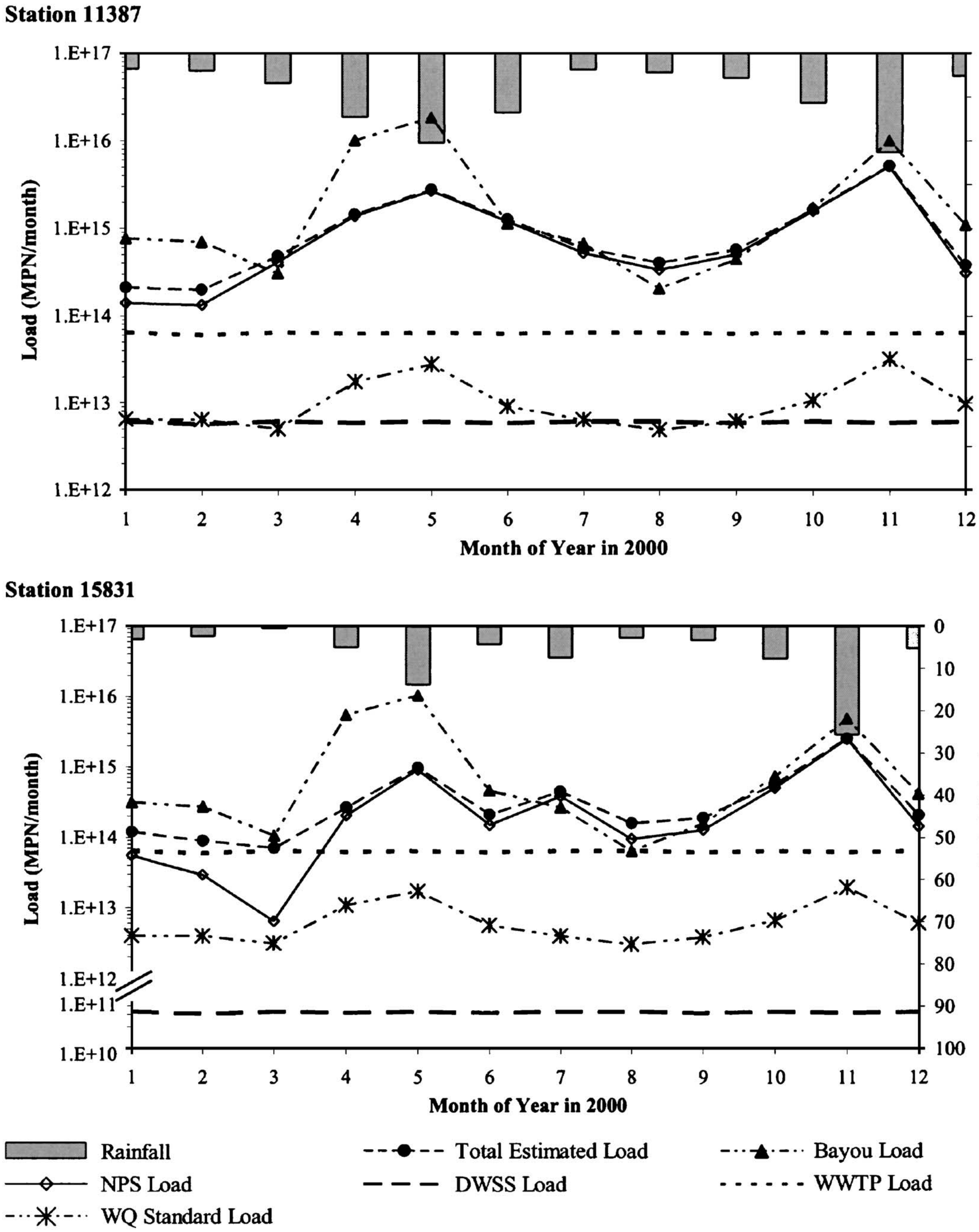

Fig. 9. Monthly loads at two stations in Whiteoak Bayou

portion of the watershed and thus would be expected to exhibit more leaks and standing water or moist conditions that provide a good habitat for bacterial growth.

The temporal distribution of loadings for the year 2000 on a monthly basis is presented in Fig. 9 for Stations 11387 and 15831. The data for Station 15831 demonstrate that the bayou load in 2000 fluctuated from 6.5×10^{13} to 1.1×10^{16} MPN/month and was generally larger than the total load from NPS, DWSS, and WWTPs, indicating another source of indicator bacteria may be present. The NPS load and bayou load, as would be expected, are correlated with the amount of rainfall. In the driest months, January–March, the WWTP load actually exceeds the load from NPS pollutants but for the remainder of the year, NPS loads are the primary source of bacterial loading to the bayou.

The data for Station 11387 generally show similar trends over time to Station 15831 but exhibit some significant differences. The loads from NPS and WWTP always exceed the water quality standard load, while the DWSS load is in close proximity to the standard. Bayou loads ranged from 2.06×10^{14} to 1.86×10^{16} MPN/month while the total estimated load fluctuated between 2.0×10^{14} and 5.16×10^{15} MPN/month. The bayou loads are always greater than the loads from WWTP and DWSS, indicating that these sources alone do not explain the bayou bacteria levels. The bayou load appears to be very strongly correlated with the NPS load, and the NPS is always the greatest source of bacterial loading, making up over 94% of the total estimated load at Station 11387. The bayou load in January, February, April, May, and November exceeds the total estimated load from all three sources. Therefore, it is likely that additional sources are present that cause the high loads during these months. It is acknowledged that there is the potential for error in these calculations; however, the estimates are intended as screening level analyses to aid in the identification of indicator bacterial sources to a highly contaminated bayou. Due to the fact that additional sources of indicator bacteria appear to be present in the watershed, further study is warranted to examine other potential sources beyond the ones explored here.

Conclusions

In summary, this paper estimated point and nonpoint bacteria loads in Whiteoak Bayou, an urban bayou in Houston. Point source loads were estimated by sampling end-of-pipe discharges while nonpoint source loads were calculated using a simple EMC-based approach. The results from sampling WWTP effluent and DWSS discharges indicate that WWTP effluent generally has very low concentrations of indicator bacteria and thus may not be a major source of bacteria to Whiteoak Bayou. The DWSS discharges, on the other hand, had much higher concentrations of indicator bacteria but the flows associated with these discharges were quite small.

The total calculated load for the watershed from effluent, DWSS, and NPS was matched to some extent with the observed load at the mouth of the bayou. Under low flow conditions, differences were observed between the in-stream loads and point source loads along the bayou, indicating other sources or an underestimation of the point source loads. In the upper part of the watershed, the point sources were lower than the estimated low flow bayou loads, indicating the presence of other sources. In the lower watershed (i.e., concrete lined), the point source loads were higher than the bayou low flow loads, possibly due to neglecting bacterial die-off. Under high flow conditions, the calculated NPS loads were lower than the in-stream loads. It is suspected that additional sources of bacteria exist during wet weather, possibly resuspended sediment or overflows, bypasses and leaks in the sewage infrastructure system.

Spatial analyses of the various bacteria sources (NPS, effluent, and DWSS discharges) indicated that NPS loads were the primary source of bacteria loading, increasing by 2 orders of magnitude from headwaters to the mouth of Whiteoak Bayou. In comparison, WWTP and DWSS loads dramatically increased from the upper to lower watershed (4 and 5 orders of magnitude, respectively), with the increases coinciding with the concrete lining of the bayou. This study indicates that the increases in DWSS loads may be a result of urbanization and development while the increased WWTP loads are likely the result of urbanization and development that focuses on multiple, smaller WWTPs rather than regionalization with larger plants. Temporal analysis indicated that annual WWTP and DWSS loads are relatively small, when compared with NPS loads. On a monthly basis, however, PS loads do occasionally exceed NPS loads, specifically in dry months. The conclusions that can be drawn from the monthly analysis are limited by the sampling approach of collecting a single sample from each plant.

In conclusion, this study demonstrates that even though point sources have been managed through the Clean Water Act of 1972, they can contribute significantly to urban streams. Over 40% of the year in Houston is extended dry weather (i.e., more than 3 days without rain), and thus point sources appear to be acting to maintain the elevated bacteria concentrations during these periods. This work also demonstrates that bacterial contamination is rather complex, influenced by spatial and temporal variation in point and nonpoint sources. Thus, efforts aimed at improving water quality should consider these variations in developing abatement or remedial strategies.

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